

Consideration of the errors inherent in mapping historical glacier positions in Austria from the ground and space (1893–2001)

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Abstract

The historical record of in situ measurements of the terminus positions of the Pasterze and Kleines Fleißkees glaciers in the eastern Alps of Austria is used to assess uncertainties in the measurement of decadal scale changes using satellite data. Topographic maps beginning in 1893, and satellite data from 1976 to 2001, were studied in concert with ground measurements to measure glacier changes. Ground measurements show that the tongue of the Pasterze Glacier receded ~ 1150 m from 1893 to 2001, while satellite-derived measurements, using August 2001 Landsat Enhanced Thematic Mapper Plus (ETM+) data registered to an 1893 topographic map, show a recession of 1300–1800 m, with an unknown error. The measurement accuracy depends on the registration technique and the pixel resolution of the sensor when two satellite images are used. When using topographic maps, an additional source of error is the accuracy of the glacier position shown on the map. Between 1976 and 2001, Landsat-derived measurements show a recession of the terminus of the Pasterze Glacier of 479 ± 136 m (at an average rate of 19.1 m a^{-1}) while measurements from the ground showed a recession of 428 m (at an average rate of 17.1 m a^{-1}). Four-meter resolution Ikonos satellite images from 2000 and 2001 reveal a shrinkage of $22,096 \pm 46 \text{ m}^2$ in the Pasterze tongue. The nearby Kleines Fleißkees glacier lost 30% of its area between 1984 and 2001, and the area of exposed ice increased by $0.44 \pm 0.0023 \text{ km}^2$, according to Landsat satellite measurements. As more recent satellite images are utilized, especially data that are geocoded, the uncertainty associated with measuring glacier changes has decreased. It is not possible to assess the uncertainty when an old topographic map and a satellite image are coregistered.

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1. Introduction

Glaciers throughout the Northern Hemisphere have been losing mass. Hölzle, Dischl, and Frauenfelder (2000) showed net mass balance decreases in 32 glaciers in the Northern Hemisphere in 10 different mountain ranges between 1980 and 1997, with the mean thickness change about -0.3 m a^{-1} . Globally, small glaciers have generally been receding on all continents with the exception of Antarctica, where the mass balance of the ice sheet is poorly

known (Dyurgerov, 2002). While much has been written about glacier changes from space, few studies show quantitative changes compared to ground measurements over a decadal time frame, precluding the establishment of measurement errors.

In this paper, we discuss changes of two glaciers in the eastern Alps of Austria: the Pasterze and the Kleines Fleißkees. More than 100 years of in situ measurements have been made on these glaciers. The excellent record of in situ measurements has permitted us to assess the accuracy of satellite-derived measurements of the Pasterze and Kleines Fleißkees glaciers, and historical ice front position changes of the Pasterze, using ground observations, Landsat and Ikonos satellite imagery, and topographic maps.

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7. Discussion and conclusions

Largely due to warm summer temperatures, both the Pasterze and the Kleines Fleißkees have receded dramatically especially since the early 1980s. We show that the recession, as measured by Landsat data, is comparable to the recession as measured on the ground (within the uncertainty of the satellite measurement technique) (Table 6).

It is sometimes impossible to measure accurately the position of a glacier terminus from space. This was demonstrated in Williams et al. (1997) in a study of glacier changes on Vatnajökull, Iceland, using Landsat data. When a glacier is in recession, debris may collect on the surface of part or all of the glacier tongue and the glacier will have a spectral reflectance similar to the surrounding moraine. This can make the exact terminus difficult to locate, especially from space. Advancing glaciers, and other receding glaciers such as tidewater glaciers with clean termini, are generally easier to measure from space (Hall, Benson, & Field, 1995; Sturm, Hall, Benson, & Field, 1991). However, even on receding glaciers with copious amounts of surficial morainal material such as that which occurs on the Pasterze Glacier, good results can be obtained by monitoring glacier changes from space as shown in this paper. On the ground, the terminus position can usually be determined by digging into the top layers of the debris, but this is a very labor-intensive activity. If ice is found, then that may represent the position of the terminus, although stagnant ice, unconnected to the glacier tongue, may further confuse the determination of the terminus.

The difference between the total recession of the Pasterze Glacier tongue estimated from the 1893 map registered to the 2001 Landsat-derived map, and the ground measurements varies from 150 to 650 m. The difference is likely due to the uncertainty of the accuracy of the Gletscherstand on the 1893 map, and the uncertainty associated with the registration of the map and ETM+ image. Also, different parts of the terminus showed different amounts of recession, and the amount of recession measured was dependent upon where on the terminus the measurement was made.

From 1976 to 2001, ground measurements show that the Pasterze Glacier tongue receded ~ 428 m (or 17.1 m a^{-1} on average), while measurements using Landsat data show a recession of 479 ± 136 m (or 19.1 m a^{-1} on average). Deterioration of the Pasterze Glacier tongue is evident even when only about 1 year intervened between Ikonos images (from September 27, 2000 to October 3, 2001) where a decrease in area of $22,096 \pm 46 \text{ m}^2$ was measured using 4-m resolution Ikonos images.

The smaller Kleines Fleißkees lost 30% of its area between 1984 and 2001, according to satellite measurements, and had an AAR of ~ 0.39 in 2001, which is indicative of a glacier with a negative mass balance.

When a high-quality topographic map and satellite image were registered, and the glacier terminus position was compared for nearly the same time period—1985 Gletscherstand and 1984 satellite image—the agreement of the terminus position was within two TM pixels (57 m), which is comparable to the ± 54 m uncertainty calculated for non-georeferenced TM images.

The Landsat database, beginning in 1972, enables decadal scale glacier changes to be measured with increasing detail, and is an important resource for measuring glacier changes and correlating those changes with regional climate changes in most glacierized areas on the Earth. Sensors like the Ikonos, with up to 1-m resolution, provide even better resolution for studying detailed changes between years, and are especially good for detailed mapping of the glacier tongue. High-quality aerial photographs also represent valuable information. However, accurate registration and comparison of aerial photographs and satellite imagery are often extremely difficult.

We have shown that uncertainties can be considerable when comparing satellite data with topographic maps, especially old maps, but that the uncertainties are much lower when recent, high-quality topographic maps are compared with satellite imagery. As extensive use is made of the three-decade long Landsat database, it is important to know the measurement errors when measuring glacier changes. These errors are getting increasingly smaller as the resolution and geocoding of the satellite images improve over time.

Table 6
Comparison of ground and Landsat-derived measurements from Iceland (Williams et al., 1997) and the Pasterze Glacier, Austria

Glacier	Years of measurement	Landsat measurement (m)	Ground measurement (m)	Difference between Landsat and ground measurement (m)
Morsárjökull, Iceland	1973–1987	$+143 \pm 136$	$+143 \pm 1$	0
Pasterze, Austria	1976–2001	-479 ± 136	-428 ± 1	51 ^a
	1984–1992	-143 ± 54	-134 ± 1	9 ^a
	1992–2001	-191 ± 54	-166 ± 1	25 ^a
Sidujökull, Iceland	1973–1987	-513 ± 136	-643 ± 1	130
Skeidarárjökull (E), Iceland	1987–1992	$+223 \pm 54$	$+276 \pm 1$	53
Skeidarárjökull (W), Iceland	1973–1987	$+257 \pm 136$	$+244 \pm 1$	13 ^a
Tungnaárjökull, Iceland	1973–1987	-1140 ± 136	-1130 ± 1	10 ^a
	1973–1992	-1413 ± 136	-1380 ± 1	33 ^a

^a Satellite measurement is higher.